Technical Report

Development of a K_{IC} Stress-Corrosion Test Specimen

Applied Research Laboratory
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DEVELOPMENT OF A K_{IC} STRESS-CORROSION TEST SPECIMEN

(39.018-002) (29) (a-ORD-NP-2) (S-23304)

March 1, 1965

By S. T. Rolfe

Approved by J. H. Gross, Division Chief

Abstract

Preliminary reports by the Naval Research Laboratory indicate that the effective fracture toughness of certain materials may be reduced if a flaw in the material can extend by stress corrosion to a critical size. Therefore, the Applied Research Laboratory initiated a study to develop a K_{IC} stress-corrosion test that would be suitable for investigating the reported phenomenon.

The results of the study indicate that by appropriate modification, the standard K_{IC} slow-bend fracture-toughness test can be used to demonstrate the effect of stress corrosion on fracture toughness. The modification consists of notching the specimen face so that plane-strain fracture can be obtained in relatively small specimens of tough materials. The fatigue-cracked area is surrounded by the appropriate corrosive environment and the specimen is dead-weight-loaded as a cantilever beam.

Preliminary results on a 12Ni-5Cr-3Mo maraging steel (yield strength of about 175 ksi and Charpy V-notch energy absorption of about 35 ft-lb) have shown that this steel failed by plane-strain fracture at values ranging from 0.8 K_{IC} at 10 hours to 0.3 K_{IC} at 400 hours when the fatigue crack was exposed under stress to synthetic sea water. To date, similar failures have not been observed in the 5Ni-Cr-Mo-V experimental HY-130/150 steel after more than 500 hours in test.

These results confirm the report that the effective fracture toughness of certain materials can be significantly reduced by the stress-corrosion extension of a sharp (fatigue) crack to the critical flaw size. Other materials of interest for submarine-hull fabrication are now being evaluated by the K_{IC} stress-corrosion-test technique.

Introduction

Susceptibility to stress-corrosion cracking is one of the primary criteria for evaluating experimental HY-180/210 steels and weldments. However, most stress-corrosion tests are not run on notched specimens and therefore are relatively long-time tests because of the slow first step in unnotched stress corrosion tests. This first step is the formation of a pit which acts as a stress-corrosion crack initiator. Moreover, materials that are nominally resistant to stress corrosion in the absence of notches or in the presence of dull notches have been observed to fail by stress-corrosion in the presence of sharp fatigue cracks. Recently, Brown of the Naval Research Laboratory reported[1)*] that by testing fatigue-cracked stress-corrosion specimens, the time to failure could be reduced markedly. This concept is similar to that used by Tiffany and Masters[2)] in determining the effect of stress intensity (K_i) to fracture-toughness (K_{IC}) ratio on time-to-fracture of fatigue-cracked specimens in a corrosive environment. Therefore, to obtain comparative information on the stress-corrosion susceptibility of promising HY-180/210 steels and weldments in a short period of time, and to evaluate such information by using the concepts of fracture mechanics, the Applied Research Laboratory applied the above concepts to the development of a K_{IC} stress-corrosion test.

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*See References.

The general requirements for such a test are:

1. The test should be a laboratory test that simulates stress-corrosion cracking in service.

2. It should be possible to test sections of actual weldments.

3. The stress-corrosion test should incorporate the failure-accelerating effects of a fatigue-cracked specimen.

4. The specimen configuration should be such that the rate of stress-corrosion cracking can be measured easily.

5. The specimen configuration should preferably be such that the results can be analyzed by using the concepts of fracture mechanics.

This report describes the development of a K_{IC} stress-corrosion test specimen, outlines the test procedures developed, and presents preliminary results on a 12Ni-5Cr-3Mo maraging steel and the 5Ni-Cr-Mo-V steel.

Early Specimen Development

Ideally, the specimen would contain a fatigue crack and would be dead-weight-loaded in a corrosive media to various percentages of its K_{IC} value (previously determined in air). If the material is susceptible to stress corrosion, the fatigue crack will extend to the critical flaw size (during which time the stress is also increasing because of the dead-weight load), and "pop-in" will occur. When pop-in occurs, the stress increases markedly (because of the dead-weight loading), and complete failure occurs. Thus, the end of the test would be well defined. Since K_{IC} is proportional

to both stress and flaw size, the behavior of different materials can be compared, even though the initial specimen sizes and fatigue cracks may not be identical. For materials too tough to exhibit plane-strain behavior, the dead-weight loading should lead to tensile fracture.

Preliminary work with the cantilever-beam-test specimen shown in Figure 1 indicated that the fatigue crack in an 18Ni (250) maraging steel did extend to the critical flaw size when immersed in synthetic sea water and a plane-strain fracture occurred. As verified by subsequent test results, and illustrated in Figure 1, the crack extended by stress corrosion. The difference in appearance of the stress-corrosion crack compared with that of the fatigue crack or the plane-strain crack is readily evident.

For steels having yield strengths less than 200 ksi, rather large specimen sizes are required to obtain valid K_{IC} results, even when the minimum depth (W) of such specimens is reduced by testing at a nominal-to-yield-strength ratio (σ_n/σ_y) at pop-in greater than 1,[3] because thickness requirements are critical if true plane-strain behavior is to be realized. Recent unpublished work,[4] however, has shown that notching the face (W) of bend specimens increases the transverse constraint, and therefore, has the same effect as increasing the thickness (B). This procedure is similar to that of the brittle-boundary concept,[5] except that artificial heat treatments are avoided. Thus, face-notched 1-inch-thick plates (B dimension) exhibit constraint approaching that of an infinitely thick

plate. Consequently, plane-strain fracture can be obtained in much smaller specimens. Figure 2 shows the effect of face notching on the fracture behavior in air of the 12Ni-5Cr-3Mo maraging steel (yield strength of 176 ksi) used in the present investigation. The results clearly indicate that for the specimen geometry employed, complete plane-strain fracture was not obtained unless the specimen was face-notched. Thus, face notching appears to be an appropriate technique for imposing the constraint required for plane-strain fracture in materials that would otherwise fail in plane stress.

A satisfactory method has been devised for calculating K_{IC} values for the fatigue-cracked, face-notched cantilever-beam specimen, Figure 3. The calculation is based on the following equation developed by Bueckner:[6)]

$$K_{IC} = \frac{6M}{B(W-a)^{3/2}} f\left(\frac{a}{W}\right)$$

where

K_{IC} = critical stress-intensity factor for plane-strain fracturing.

M = bending moment.

B = specimen width (for face-notched specimens, use net width, B_N).

W = specimen depth.

a = crack length (including fatigue crack).

$f\left(\frac{a}{W}\right)$		$\frac{a}{W}$
0.36	for	0.05
0.49		0.10
0.60		0.20
0.66		0.30
0.69		0.40
0.72		0.50
0.73		0.60 (and larger)

Bueckner's equation permits calculation of K_{IC} values for cantilever-beam specimens because the K_{IC} value is expressed as a function of the bending moment (M) and is, therefore, applicable to any type of bend specimen. In contrast, the more widely used expression developed by Srawley and Brown[7] applies only to three-point-loaded bend specimens. An analysis[4] of K_{IC} values calculated by Bueckner's equation from data obtained from cantilever-beam specimens showed that the values agreed quite well with those calculated by Srawley and Brown's equation from data obtained on three-point-loaded bend specimens.

Thus, the specimen shown in Figure 3 meets the requirements for a K_{IC} stress-corrosion test specimen.

Test Setup and Procedure

A schematic drawing showing the various components of one of the twelve test stands is presented in Figure 4, and an overall view of the test rack is presented in Figure 5. The method of introducing a corrosive environment around the specimen is illustrated in Figure 6.

The test procedure generally followed is:

1. After heat treatment, the specimens are machined and fatigue-cracked 0.05 to 0.10 inch.

2. A specimen is dead-weight-loaded to failure in air to determine K_{IC}. For steels whose strength and toughness are such that tensile fracture occurs prior to plane-strain fracture, the fracture stress is determined. As

will be described in a subsequent report, close agreement exists between K_{IC} values determined from specimens dead-weight-loaded to failure and specimens tested in the more conventional three-point-bending setup.

3. Specimens are dead-weight-loaded in synthetic sea water (ASTM Designation D1141-52) to various percentages of K_{IC} or fracture load and the times to failure recorded. For materials susceptible to stress corrosion, the fatigue crack extends by stress corrosion to the critical flaw size, after which failure occurs by sudden fracturing of the remaining cross section. Although the failures are obvious, dial gages can be used to measure deflections during testing (to determine rate of stress-corrosion cracking) and microswitches are used to interrupt a time circuit at failure.

4. A single specimen is loaded to 0.8 to 0.9 K_{IC} (or 0.8 to 0.9 fracture load) in air as a control specimen.

Initial Test Results

Materials

Twenty-five 1-inch-deep specimens (as shown in Figure 3) of a 12Ni-5Cr-3Mo steel were prepared for the initial tests. In addition, 1- and 2-inch-deep specimens of the 5Ni-Cr-Mo-V steel were prepared to determine whether lower strength, higher toughness materials were susceptible to failure by stress-corrosion of fatigue cracks. The material investigated was obtained from a 20-ton (12Ni-5Cr-3Mo) or an 80-ton (5Ni-Cr-Mo-V) commercial electric-furnace heat. A chemical check analysis of the steels is presented in Table I, and the mechanical properties are presented in Table II.

Preliminary Results

As an example of the type of information being obtained with the K_{IC} stress-corrosion test procedure, preliminary results on the 12Ni-5Cr-3Mo maraging steel are presented in Tables III and IV and preliminary results on the 5Ni-Cr-Mo-V steel are presented in Table V.

The K_{IC} value of the 12Ni-5Cr-3Mo steel was 153 ksi $\sqrt{\text{inch}}$ (Specimen 4, Table III). Specimen 5 was dead-weight-loaded to 0.6 K_{IC} in air and has not failed after 600 hours loading. Specimens 6, 7, and 8 were dead-weight-loaded to 0.6, 0.48, and 0.3 K_{IC} in synthetic sea water, and the failure times were 25, 140, and 408 hours, respectively.

If the critical stress-intensity factor for plane-strain fracture is calculated on the basis of the total flaw size that exists at the time of fracture (K_f), the results show that the inherent fracture toughness of the material has not changed significantly. Thus, the failure at K_i values lower than the K_{IC} value in air simply indicates that the initial fatigue crack has been extended by stress corrosion to the critical flaw size for the lower imposed stress. However, because the crack extension by stress corrosion can occur in relatively short times, the effective fracture-toughness design value can be reduced by exposure of material to a stress-corrosive environment. In effect, the K_i value expresses the critical stress-intensity factor for plane-strain fracture when the material is exposed to an environment that can cause extension of a fatigue crack by stress

corrosion. Thus, the K_i value, which is calculated on the basis of the size of the original fatigue flaw, has significance. As shown in Table III, the K_i value becomes time dependent because stress corrosion is a time-dependent phenomenon.

Similar results for another plate of the 12Ni-5Cr-3Mo steel are presented in Table IV. The K_{IC} was 148.5 ksi $\sqrt{\text{inch}}$, and specimens were dead-weight-loaded to values of 0.82 to 0.3 K_{IC} in synthetic sea water. Failure times ranged from 5.5 to more than 480 hours (test still in progress). In addition, a control specimen was dead-weight-loaded in air to 0.8 K_{IC} and has not failed after 600 hours under load.

The results, Figure 7, show that a linear relationship exists (for this steel) between K_i/K_{IC} and log time to some limiting value of K_i/K_{IC}.

Typical photomicrographs of two specimens are presented in Figure 8. The fatigue, stress-corrosion, and plane-strain portions of the fracture surfaces are evident. A fractograph of a stress-corrosion-cracked surface, showing areas of stress-corrosion attack, is compared with an unattacked plane-strain crack surface in Figure 9.

Photomacrographs of a 5Ni-Cr-Mo-V and a 12Ni-5Cr-3Mo plain-plate specimen dead-weight-loaded to failure are shown in Figure 10. The strength and toughness level of the 12Ni-5Cr-3Mo steel was such that pop-in occurred and failure occurred by plane strain. The strength and toughness level of the 5Ni-Cr-Mo-V steel was such that although shear-lip formation was

suppressed by the face notches, plane-strain conditions did not exist and failure occurred by tensile fracture. However, in both cases, because of the dead-weight loading, the failures were complete. Thus, even though plane-strain behavior (K_{IC}) may not occur in all specimens face-notched and dead-weight-loaded to failure, results can be compared as a percentage of fracture stress (σN_f) as well as a percentage of K_{IC}.

Preliminary results on the 5Ni-Cr-Mo-V steel are presented in Table V and show that no stress-corrosion failures have occurred to date (>500 hours), even at values as high as $0.85\sigma N_f$.

Summary

The present report describes the development of a K_{IC} stress-corrosion test specimen. The salient features of this test specimen may be summarized as follows:

1. The test specimen is a face-notched slow-bend specimen that exhibits either plane-strain failure or tensile failure (for high toughness steels) without shear-lip formation.

2. Either plain plates or sections of actual weldments may be tested.

3. The specimen is sharply notched (fatigue-cracked) to obtain comparative information on stress-corrosion cracking in the shortest possible time.

4. The specimen can be immersed in various solutions (synthetic sea water is currently being used) and dead-weight-loaded to any percentage of K_{IC} or tensile-fracture stress.

5. If the material being studied is susceptible to stress-corrosion cracking, slow crack growth occurs until the flaw size and stress level are such that either plane-strain or tensile fracture occurs, depending on the strength and toughness of the material being studied. Thus, the end of the test is well defined.

6. Preliminary results indicate that the effective K_i value of 12Ni-5Cr-3Mo maraging steel may be significantly lower in synthetic sea water than in air because of stress-corrosion cracking. To date, a similar reduction in the fracture stress value of the 5Ni-Cr-Mo-V steel has not been observed.

These preliminary test results indicate that the test procedure described in this report can be used to determine the susceptibility of materials to stress-corrosion cracking in relatively short periods of time.

Future Work

Other materials of interest for submarine-hull fabrication are now being evaluated by the K_{IC} stress-corrosion-test technique that has been developed.

References

1. B. F. Brown, "Stress-Corrosion Cracking and Corrosion Fatigue of High-Strength Steels," Problems in the Load-Carrying Application of High-Strength Steels, DMIC Report 210, October 26-28, 1964, pp. 91-102.

2. C. F. Tiffany and J. N. Masters, "Applied Fracture Mechanics," Paper presented before the Symposium on Fracture Toughness Testing, sponsored by The American Society for Testing and Materials, Chicago, Illinois, June 23-24, 1964.

3. R. A. Brand and S. T. Rolfe, "Procedures for Determining K_{IC} for 180/210 Ksi Yield-Strength Steels," Applied Research Laboratory Report No. 40.018-002(23), (S-23302), December 1, 1964.

4. S. T. Rolfe, "Effect of Face Notching on K_{IC} Testing," Applied Research Laboratory Report (to be published).

5. R. P. Wei and F. J. Lauta, "Plane Strain Fracture Toughness Evaluation Using Carbonitrided SEN Specimens," To be published in Materials Research and Standards, 1965.

6. P. C. Paris and G. C. Sih, "Stress Analysis of Cracks," Department of Mechanics, Lehigh University, June 1964.

7. J. E. Srawley and W. F. Brown, Jr., "Fracture Toughness Testing," NASA TM X-52030, Paper presented before the Symposium on Fracture Toughness Testing sponsored by The American Society for Testing and Materials, Chicago, Illinois, June 23-24, 1964.

Table I

Composition of Steel Investigated—Percent
(Check Analysis)

Heat No.	C	Mn	P	S	Si	Ni	Cr	Mo	Co	V	Cb	Ti	Al**	Al+	B	Zr	N	O
12Ni-5Cr-3Mo Steel																		
X14689	0.023	0.088	0.004	0.008	0.094	12.10	5.21	2.86	ND*	ND	ND	0.24	0.38	ND	0.0037	<0.01	0.009	0.001
5Ni-Cr-Mo-V Steel																		
X53957	0.105	0.78	0.007	0.004	0.23	5.01	0.55	0.55	ND	0.52	ND	ND	0.014	0.019	ND	ND	0.011++	ND

*Not determined.
**Acid soluble.
+Total.
++Kjeldahl determination.

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Table II

Mechanical Properties of Steels Investigated

Property	12Ni-5Cr-3Mo Plate No. 59805*	12Ni-5Cr-3Mo Plate No. 59806**	5Ni-Cr-Mo-V Plate No. 0253322A**
Yield strength (0.2% offset), ksi	176	171	135
Tensile strength, ksi	183	178	142
Reduction of area, %			
At maximum load	3.9	5.5	10.5
At fracture	60.4	62.8	71.1
Elongation in 1 inch, %			
At maximum load	3.0	3.0	7.0
At fracture	15.5	15.5	20.0
Charpy V-notch energy absorption, ft-lb			
At 0 F	34.5	31.0	103
At +80 F	36.0	35.0	112

*Rolled from 2 inches to 1 inch at the Applied Research Laboratory.
**One-inch-thick plate as-received from mill.

Table III

Results of 12Ni-5Cr-3Mo K_{IC} Stress-Corrosion Tests (Plate 59806)

Specimen	W, inches	B, inches	B_N, inches	a, inches	P, pounds	L, inches	K_i, ksi $\sqrt{\text{inch}}$	σ_N, ksi	K_i/K_{IC}	a_{cr}, inches	K_f, ksi $\sqrt{\text{inch}}$	σ_{N_f}, ksi	Time, hours	Environment
4	1.0	1.0	0.76	0.33	526	30.0	153.0*	278.0	1.00	—	—	—	—	Air
5	1.0	1.0	0.77	0.28 (est)	371	30.0	92.5	168.0	0.60	—	—	—	~600	Air
6	1.0	1.0	0.77	0.28	371	30.0	92.5	168.0	0.60	0.45	148.5	287	25	Synthetic Sea Water
7	1.0	1.0	0.77	0.30	280	30.0	74.0	134.0	0.48	0.53	147.0	297	140	Synthetic Sea Water
8	1.0	1.0	0.77	0.28	187	30.0	46.5	84.5	0.30	0 3	143.0	322	408	Synthetic Sea Water

*K_{IC} = 153 ksi $\sqrt{\text{inch}}$.

K_i = Value of K_I calculated from fatigue-crack size (a)

K_f = Value of K_I calculated from final crack size (a_{cr})

σ_N = initial nominal stress

σ_{N_f} = final nominal stress

Table IV

Results of 12Ni-5Cr-3Mo K_{IC} Stress-Corrosion Tests (Plate 59805)

Specimen	W, inches	B, inches	B_N, inches	a, inches	P, pounds	L, inches	K_i, ksi $\sqrt{\text{inch}}$	σ_N, ksi	K_i/K_{IC}	a_{cr}, inches	K_f, ksi $\sqrt{\text{inch}}$	σ_{Nf}, ksi	Time, hours	Environment
M	1.00	0.83	0.63	0.32	444	30.0	151.5*	275	—	—	—	—	—	Air
D	1.00	0.83	0.63	0.30	461	30.1	149.0*	270	—	—	—	—	—	Air
E	0.91	0.83	0.63	0.29	375	29.8	145.0*	272	—	—	—	—	—	Air
F	0.91	0.83	0.63	0.28	292	29.8	110.0	208	0.74	0.35	136	265	12	Synthetic Sea Water
G	1.00	0.83	0.63	0.30 (est)	370	29.8	118.0	214	0.80	—	—	—	>600	Air
H	1.00	0.83	0.63	0.28	318	29.9	95.9	175	0.65	0.42	143	270	78	Synthetic Sea Water
I	1.00	0.83	0.63	0.33	277	29.8	95.6	176	0.64	0.45	136	252	26	Synthetic Sea Water
J	1.00	0.83	0.63	0.29	225	30.1	70.6	128	0.48	0.52	140	280	115	Synthetic Sea Water
M	0.91	0.83	0.63	0.28	223	29.3	82.5	157	0.56	0.46	149	308	21	Synthetic Sea Water
O	0.80	0.83	0.62	0.28	130	30.0	62.5	127	0.42	0.4[illegible]	13[illegible]	31[illegible]	14[illegible]	Synthetic Sea Water
P	0.80	0.83	0.62	0.28 (est)	85	30.0	45.0	91	0.30	—	—	—	48[illegible]	Synthetic Sea Water
Q	1.00	0.83	0.63	0.29	389	30.0	122.0	221	0.82	0.34	140	25[illegible]	5.5	Synthetic Sea Water

*Average K_{IC} value = 148.5

Table V

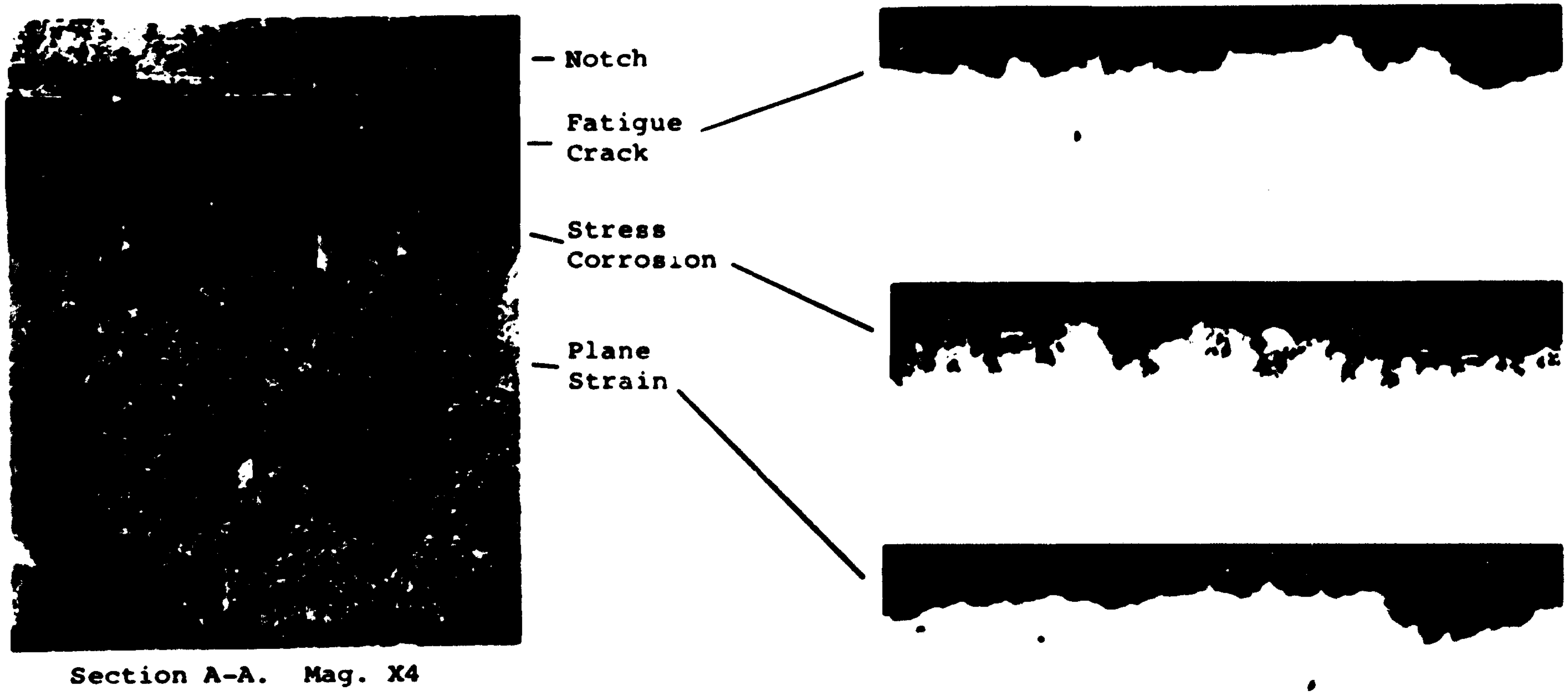
Results of 5Ni-Cr-Mo-V K_{IC} Stress-Corrosion Tests (Heat 53957)

Specimen	W, inches	B, inches	B_N, inches	a, inches	P, pounds	L, inches	σ_i, ksi	σ_i/σ_{N_f}	a_{cr}, inches	σ_{N_f}, ksi	Time, hours	Environment
5N2	0.97	0.91	0.71	0.30	568	30	322*	1.00	—	—	—	Air
5N11	0.97	0.91	0.71	0.30	556	30	314*	1.00	—	—	—	Air
5N10	0.97	0.91	0.71	0.30 (est)	445	30	273	0.85	—	—	>500	Synthetic Sea Water
5N12	0.97	0.91	0.71	0.30 (est)	389	30	241	0.75	—	—	>500	Synthetic Sea Water
5N5	0.96	0.91	0.71	0.30 (est)	445	30	273	0.85	—	—	>500	Air
5N9	0.97	0.91	0.71	0.30 (est)	349	30	197	0.62	—	—	>500	Synthetic Sea Water
5N3	0.97	0.91	0.71	0.30 (est)	289	30	163	0.51	—	—	>500	Synthetic Sea Water

σ_i = initial nominal stress

σ_{N_f} = final nominal stress

*Average $\sigma_{fracture}$ = 318



Section A-A. Mag. X4

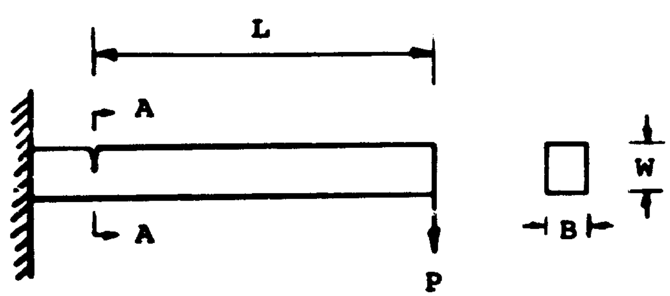


Figure 1. Preliminary test on an 18Ni (250) maraging steel.

P-4839A-1
18-328A-1, A-2, A-3

(39.018-002)(29)

Figure 1

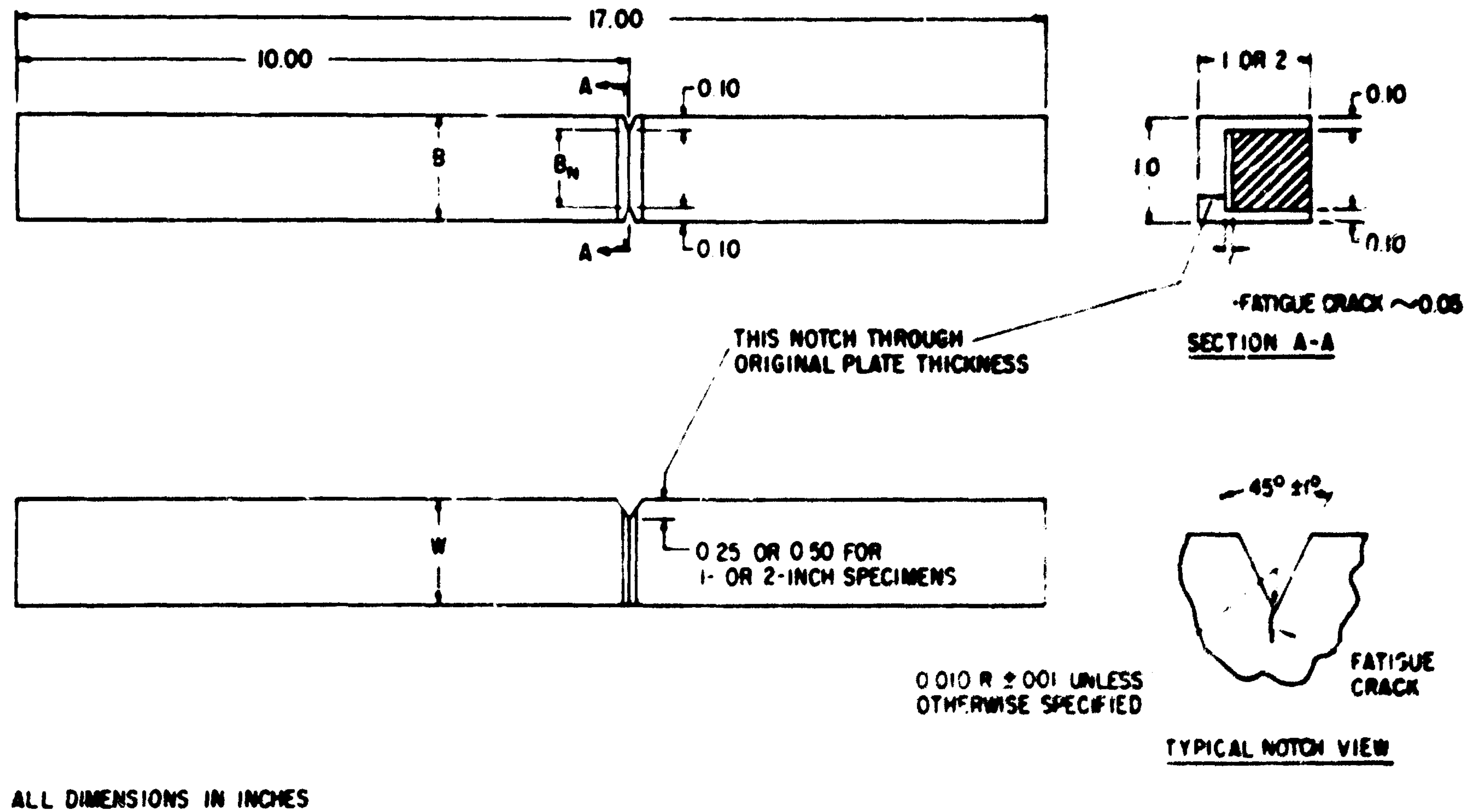
Face notched. (X2)

Smooth face. (X2)

Figure 2. Effect of face notching on suppression of shear lips in 12Ni-5Cr-3Mo steel.

P-5025A-3
P-5025A-5

(39.018-002)(29)



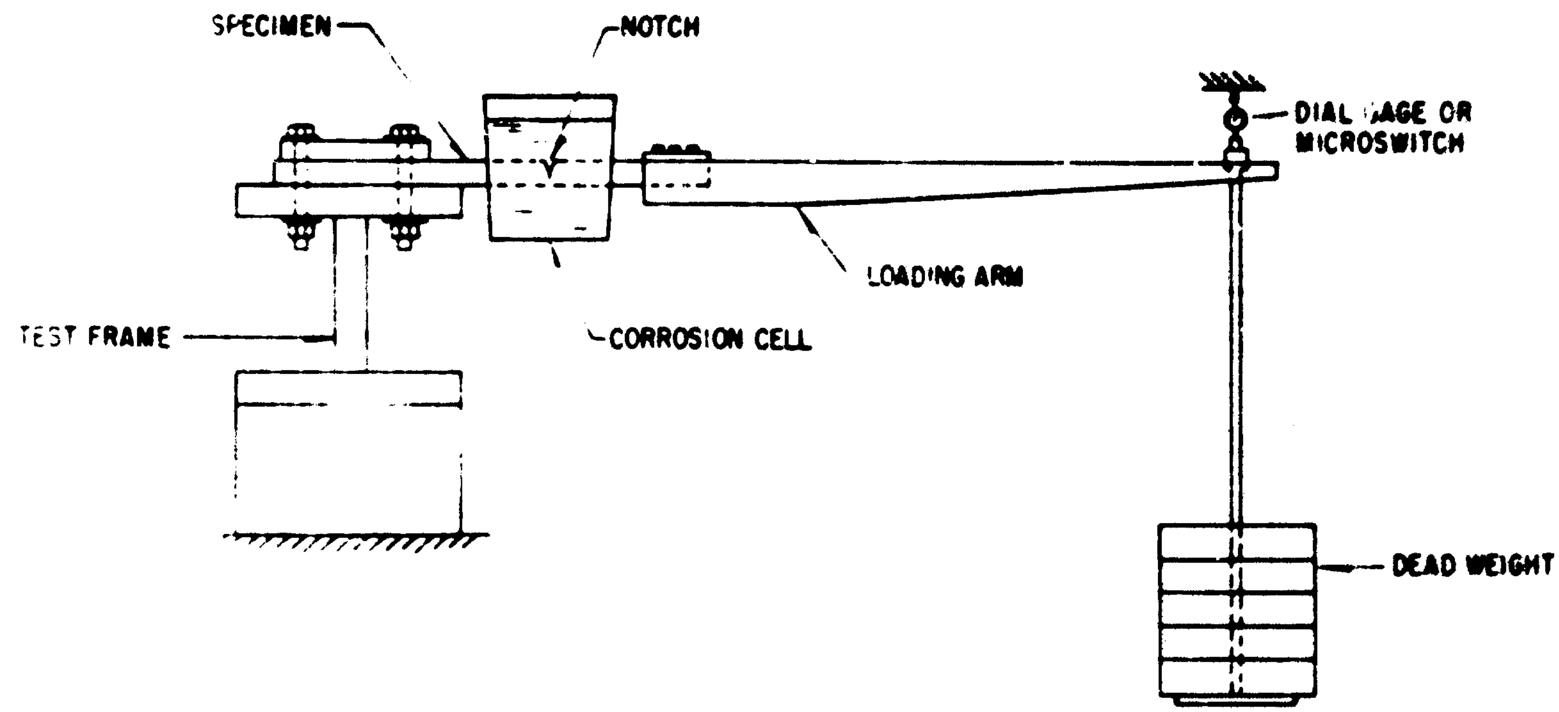
K_{IC} STRESS-CORROSION TEST SPECIMEN

MM | STP | JHG

ARL 18-558

UNITED STATES STEEL CORPORATION
APPLIED RESEARCH
PITTSBURGH, PA

FIGURE NO 3



SCHEMATIC DRAWING OF K_{Ic} STRESS-CORROSION TEST SPECIMEN AND FIXTURES

UNITED STATES STEEL CORPORATION
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PITTSBURGH, PA.

18-559

FIGURE NO 4

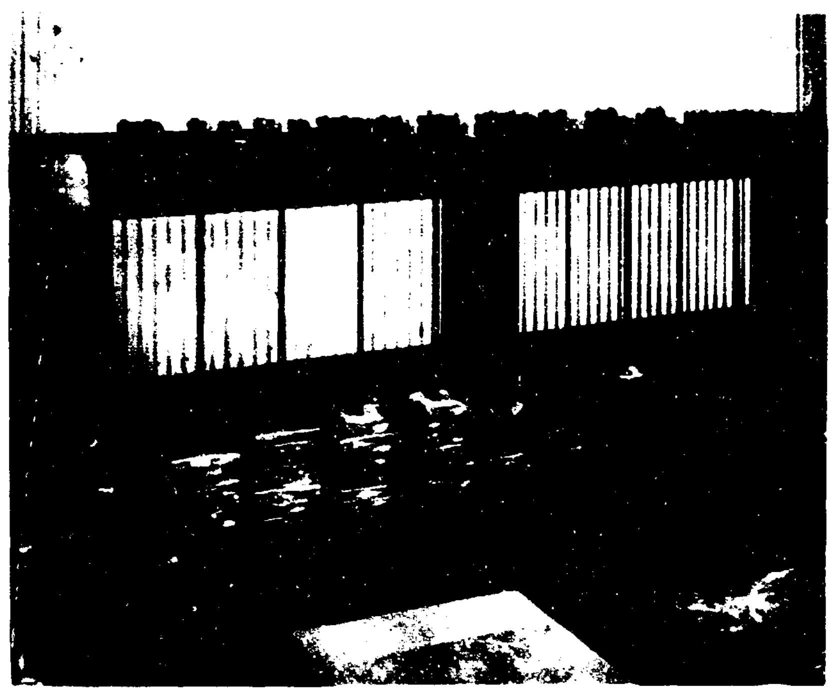


Figure 5. K_{IC} stress-corrosion test stand.

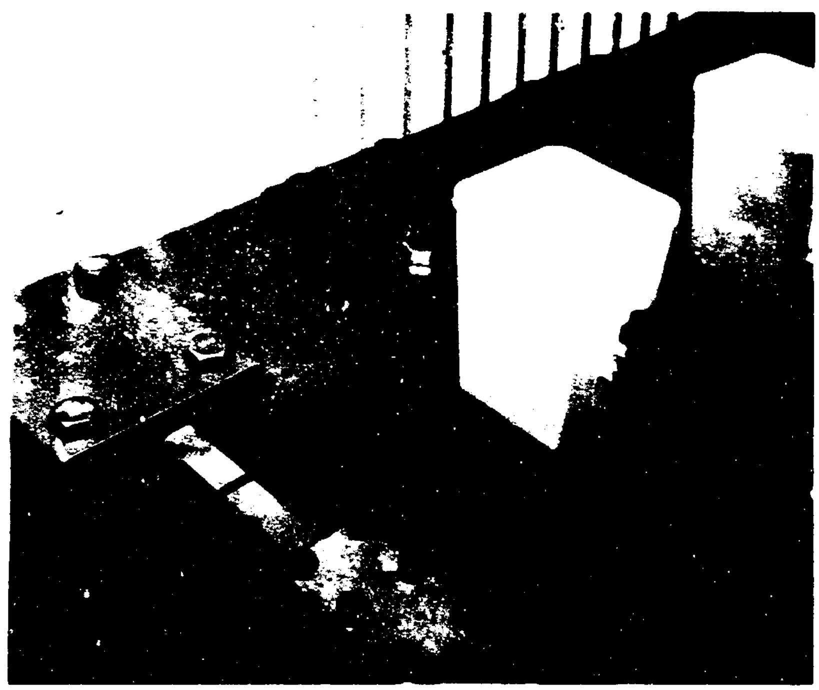
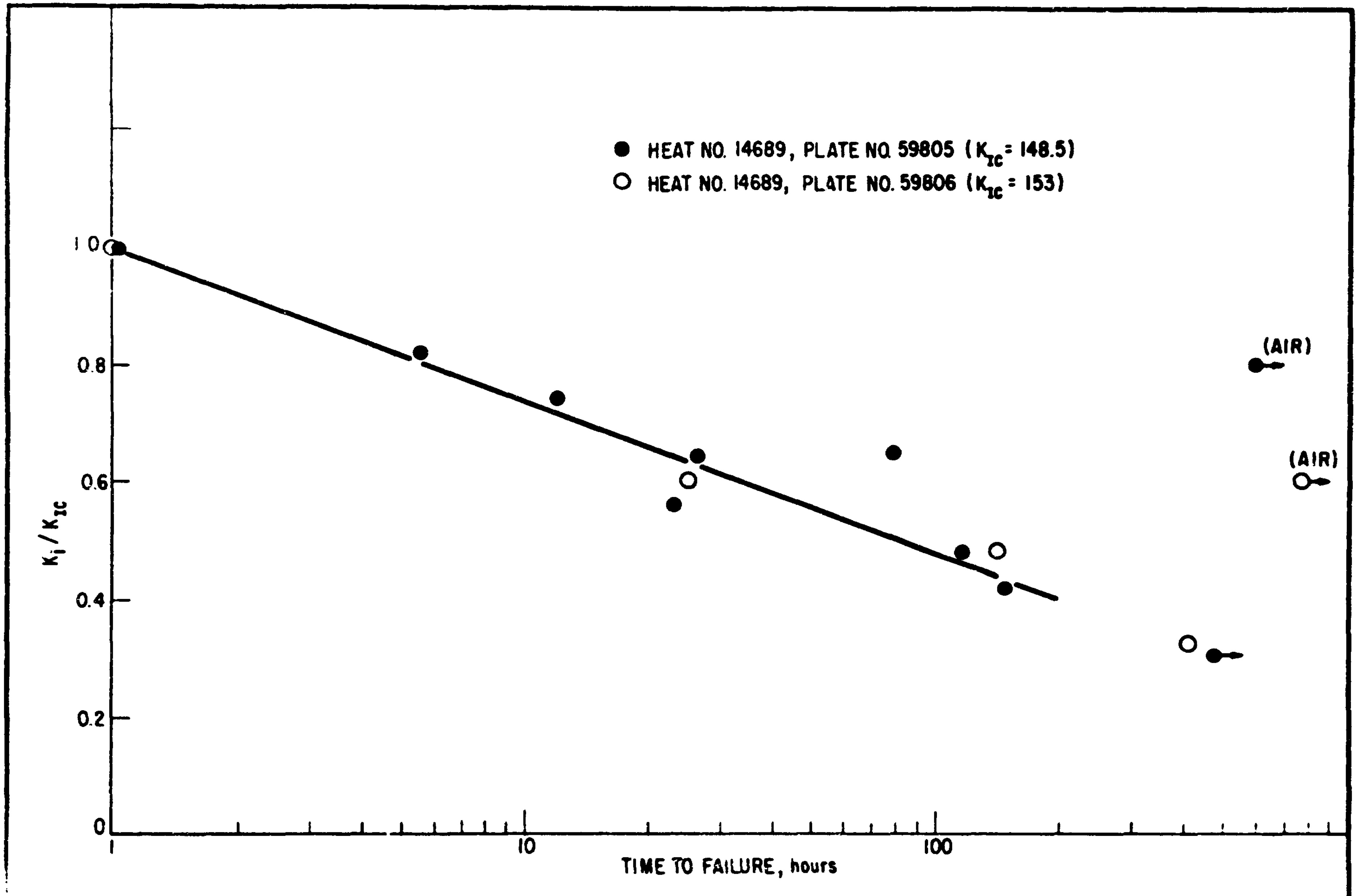


Figure 6. Close-up of K_{IC} stress-corrosion specimens in air and synthetic sea water.



K_i / K_{IC} STRESS-CORROSION RESULTS FOR 12 Ni-5 Cr-3 Mo STEEL TESTED IN SYNTHETIC SEA WATER

DRAWN BY M.M.	CHK'D BY S.T.R.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION	FIGURE NO.
ARL 18-560		39.0-002(29) 3/16/65	APPLIED RESEARCH PITTSBURGH, PA	7

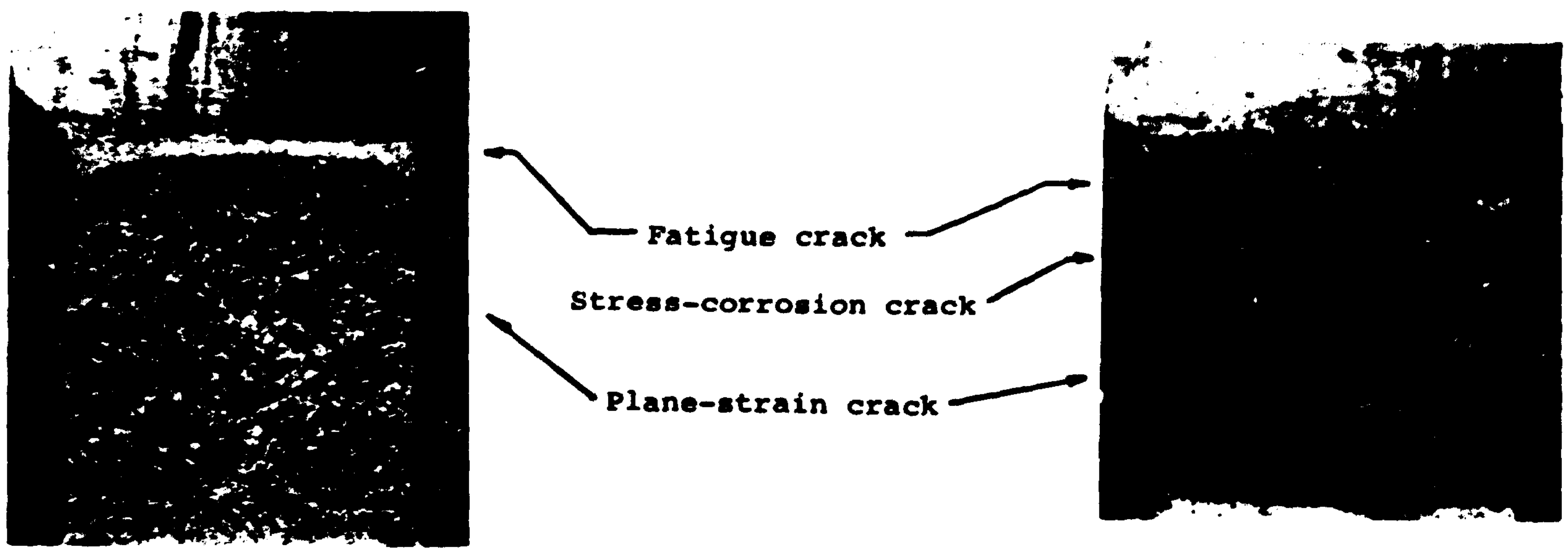
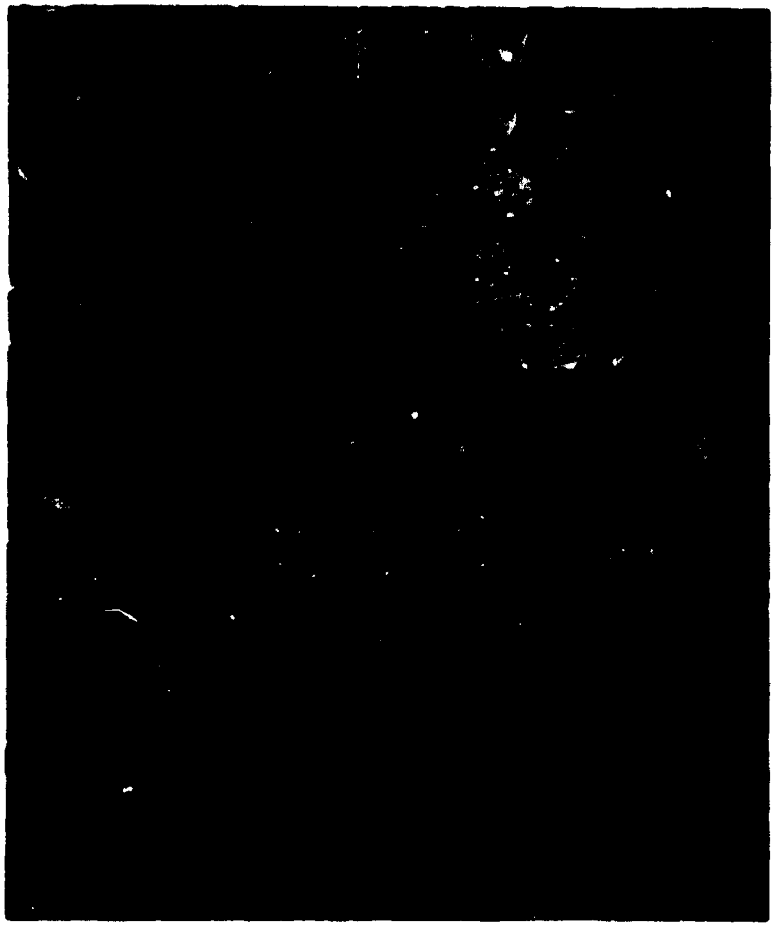
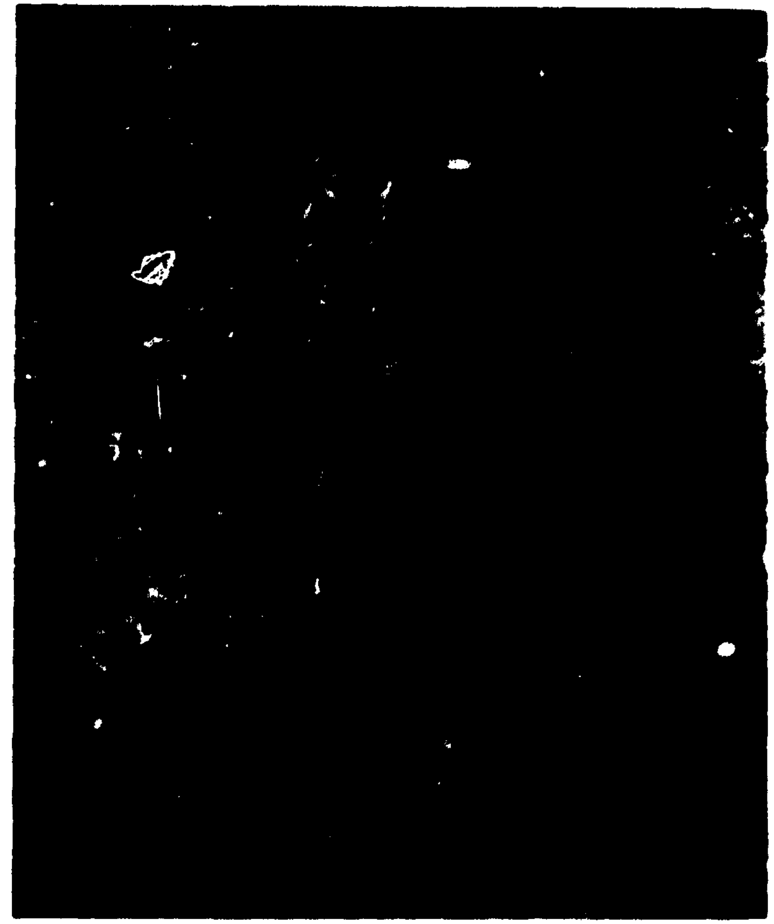


Figure 8. Typical 12Ni-5Cr-3Mo K_{IC} stress-corrosion specimens tested in air and synthetic sea water.

P-5025A-1
P-5025A-2



Plane strain (air).



Stress corrosion (synthetic sea water).

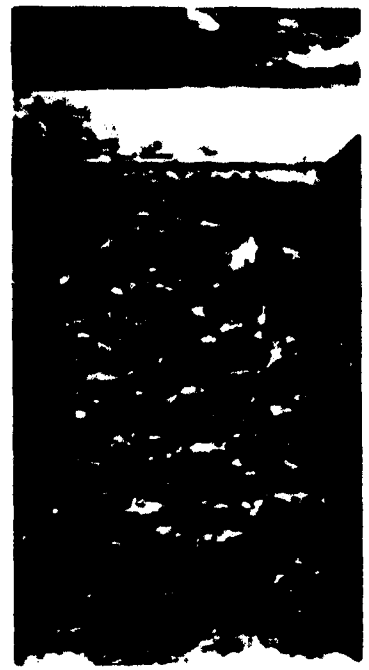
Figure 9. Fractographs of 12Ni-5Cr-3Mo steel showing difference in plane-strain fracture surface and stress-corrosion crack surface (X8000).

18E-329A-1
18E-328A-1

(39.018-002)(29)

Figure 9

12Ni-5Cr-3Mo
K_{IC} failure.
(X2)



5Ni-Cr-Mo-V
tensile failure.
(X2)

Figure 10. Typical fracture appearance of face-notched specimens of 12Ni-5Cr-3Mo steel and 5Ni-Cr-Mo-V steel.

P-5025A-3
P-5025A-4